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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

LIFE CYCLE COST ESTIMATE OF LSD(X)

by

Allison Hills

June 2012

Thesis Advisor:
Second Reader:

Daniel Nussbaum
Gregory Mislick

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LIFE CYCLE COST ESTIMATE OF LSD(X)

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis develops a model that provides a credible and reliable rough order magnitude (ROM) Life Cycle Cost Estimate (LCCE) for a newly constructed U.S. Navy Dock Landing Ship, LSD(X), over the various phases of design, procurement, and operations and support costs. The Systems Engineering Analysis (SEA) Curriculum at the Naval Postgraduate School (NPS) will use this estimate to help establish the costs of the proposed alternatives for LSD(X). This study also includes a cost benefit analysis through the comparison of LSD(X) to an alternative variant LSD(XB). The comparison examines how the baseline ROM LCCE of LSD(X) is affected by changes in technical parameters such as beam, number of LCACs, troop size, crew size and cargo capacity. Ultimately, this thesis provides a useful tool to aid decision makers in selecting the most cost effective alternative for the LSD(X) fleet for the expected 30 year operational period.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAS	Amphibious Assault Ship
AOR	Auxiliary Oiler Replenishment
CBO	Congressional Budget Office
CER	Cost Estimating Relationship
CI	Confidence Interval
DAU	Defense Acquisition University
DoD	Department of Defense
FY	Fiscal Year
LCAC	Landing Craft Air Cushion (U.S. Navy)
LCCE	Life Cycle Cost Estimate
LHA	Landing Helicopter Assault (U.S. Navy)
LHD	Landing Helicopter Dock (U.S. Navy)
LPD	Landing Platform Dock (U.S. Navy)
LPH	Landing Platform Helicopter
LRIP	Low Rate Initial Production
LSD	Landing Ship Dock (U.S. Navy)
LSD (X)	Follow-on Landing Ship Dock (U.S. Navy)
LT	Long Tons
NATO	North Atlantic Treaty Organization
NCCA	Naval Center for Cost Analysis
O&S	Operations and Support
OPNAV	Office of the Chief of Naval Operations
R ²	Coefficient of Determination

R&D	Research and Development
RAND	Research and Development Corporation (Santa Monica, CA)
RTO	Research and Technology Organization
ROM	Rough Order Magnitude
SAS	Systems Analysis and Studies
SCN	Ship Conversion Navy
SEA	Systems Engineering Analysis Curriculum at Naval Postgraduate School
SWBS	Ship's Work Breakdown Structure
USN	United States Navy
WSARA	Weapons Systems Acquisition Reform Act (2009)

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EXECUTIVE SUMMARY

When determining the most cost effective shipbuilding programs, the U.S. Navy relies on Life Cycle Cost Estimates (LCCE) to evaluate the expected costs of a proposed system. These estimates are developed for each proposed system in order to aide decision makers in eliminating overly risky and costly programs and deciding between the remaining alternatives. In the early stages of an acquisition program, the LCCEs are developed on loosely defined parameters and must be robust to allow for changes in design specifications.

In the case of the Dock Landing Ship, LSD(X), the Office of the Chief of Naval Operations, OPNAV N8F, is determining the best possible means to maintain an LSD fleet able to meet the mission requirements in the distant future. Because the current LSD fleet is scheduled to be decommissioned over the next 20 to 30 years, mission capability gaps will become prevalent if not addressed. The Systems Engineering Analysis Curriculum students have been requested to delve into these capability gaps and develop a cost effective proposal that ensures that these gaps are not realized.

This thesis focuses on the proposal to build LSD (X) -- a new amphibious ship class to replace the current LSD ships. Because LSD (X) is in its design phase with little engineering data and specifications available, the appropriate cost estimating approach is to develop a model through parametric analysis. The Ships Work Breakdown Structure (SWBS) is used as a guide to develop materiel cost and labor hour estimates for specific sections of the proposed LSD(X). Using standard regression techniques, a number of parametric cost models were constructed at each of the nine SWBS levels based on historical amphibious ship procurement data. An aggregate cost model, combining the best performing models at each SWBS level, was then constructed to help determine the cost ramifications of adjustments in the ship's technical parameters. This cost model will be presented to the SEA Curriculum students to aid them in choosing the most cost effective means of meeting the requirements outlined in the capabilities-based assessment.

The aggregate cost model was then applied to the technical parameters assigned for LSD(X), as well as for a larger alternative variant LSD(XB), by the Systems Engineering Analysis curriculum students. After developing lead ship cost estimates, Monte Carlo Simulation was employed to identify the 80th percentile value of the LCCE Cumulative Distribution Function (CDF) in order to ensure compliance with the Weapons Systems Acquisition Reform Act of 2009.

After conducting 100,000 simulations, the 80th percentile lead ship estimates in FY12\$ for LSD(X) and LSD(XB) are as follows:

- LSD(X) \$660M
- LSD(XB) \$829M

These estimates do not include design costs, and they include the construction cost of the lead ship only.

In order to generate the LCCE, the design costs, procurement costs, and the Operating and Support (O&S) costs for each ship must be considered. When these figures were calculated, the resulting LCCE for LSD (X) is \$20.37 billion and \$23.42 Billion for LSD(XB), in FY\$12 dollars. Included in these LCCEs is the assumption that 11 new construction LSD ships will be purchased at an interval of one ship every other year over a 22 year time frame and that each ship will operate for 30 years.

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I. INTRODUCTION

A. PROJECT BACKGROUND

The U.S. Navy currently has 12 operational Dock Landing Ships (LSD) designed to support amphibious operations worldwide. The first LSD of the Whidbey Island Class was commissioned in 1985 and was followed by the last of the Harper's Ferry Class in 1998. These LSDs are considered to be mid-life and because of the extensive time period required to develop and build a replacement follow-on LSD, the U.S. Navy, specifically OPNAV N8F of the Chief of Naval Operations (CNO) office, has requested a LSD fleet capabilities-based assessment. This assessment will focus on:

- Filling capability gaps (including improving declining materiel condition and readiness, replacing obsolete equipment, and reducing Total Ownership Costs)
- Developing designs that meet amphibious mission performance criteria, and
- Developing Life Cycle Cost Estimates (including Design costs, Procurement, and Operating and Support costs) of these designs.

As part of OPNAV N8F's request, an independent evaluation for LSD capabilities-based assessment to develop designs that meet amphibious mission performance criteria will be conducted by the Systems Engineering Analysis (SEA) curriculum students at the Naval Postgraduate School.

Embedded in the fleet recapitalization study is the need for a credible and reliable rough order of magnitude (ROM) life cycle cost estimate (LCCE) on the designs developed for the follow-on LSD. LCCEs are the expected costs associated with a particular program from "cradle to grave" including: Design, Procurement, and Operation and Support (O&S) costs. These estimates give decision makers the tools required to help with ship design and with the selection of the most cost effective alternative.

Ultimately, this thesis provides a useful tool to aid decision makers in selecting the most cost effective alternative for the LSD(X) fleet for the expected 30 year operational period.

B. THESIS OBJECTIVE

This thesis develops a model that provides a credible and reliable rough order magnitude (ROM) Life Cycle Cost Estimate (LCCE) for a newly constructed LSD(X) over the various phases of design, procurement, and operations and support costs. The SEA Curriculum will use this model to estimate the costs of the proposed alternatives for LSD(X). This study also includes a cost benefit analysis through the comparison of LSD(X) to an alternative variant LSD(XB). The comparison examines how the baseline ROM LCCE of LSD(X) is affected by changes in technical parameters such as beam, number of LCACs, troop size, crew size and cargo capacity.

C. METHODOLOGY OVERVIEW

Because very little specific information is known about the projected designs of the follow-on LSD, a ROM estimate classification, comprised of factored historical information, will be used in the LCCE.¹ The five common methods for developing cost estimates are estimates based on:

- Analogy
- Parametric Modeling
- Engineering or Build up Method
- Extrapolation by Actuals
- Expert Opinion

These methods permit the cost estimator to bridge the gap between historical data and future costs. The selection of the method depends on the current phase of the project, along with the statistical properties and logical relationships of the data.

¹ Naval Postgraduate School. *Unpublished Course Material for Course OA4702: Cost Estimation*. Naval Postgraduate School, 2012.

Because the follow-on LSD is in the concept and technology stage of development, both the Analogy and Parametric approaches are appropriate for use in the initial cost estimating process. An advantage to the Analogy approach would be that it is quick and therefore inexpensive to generate, but it is more uncertain because it is based on a single historical data point and reliant on a single system that is most analogous to the new system as its basis for comparison. The Parametric approach uses regression analysis to establish Cost Estimating Relationships (CERs). These CERs help estimate costs of designs which have specific system design parameters. Table 1 displays the definitions and appropriate usage of the Analogy and Parametric methods as well as the other three common cost estimating methodologies.

Type	Definition	When Used	Method
Analogy	Forecasting the cost of a future weapon system or ship based on the historical cost of a similar or analogous item.	Early in the cost estimating process or when only one system to compare is available	An adjustment is applied to the cost of analogous system based upon chosen parameter metrics
Parametric	Establishes a statistically valid relationship among the dependent variables and/or various physical and performance characteristics.	System Development and Demonstration Phase	Apply statistical methods to the costs of two or more analogous systems.
Engineering/ Build-up	Detailed build-up of labor, materiel and overhead costs	Low Rate Initial Production (LRIP)	Estimate costs of discrete tasks and systems by lowest cost level and sum by Work Breakdown Schedule (WBS)
Extrapolation by Actuals	An extrapolation of current program costs	Late in Program during Low Rate Initial Production (LRIP) and Full Rate Productions	Use trends from current contract to estimate final system costs
Expert Opinion	One or more expert opinions provide the basis for the cost estimate	Used to support all types of estimating methodologies	Experts estimate parameter impacts along with impacts to labor and materiel costs

Table 1. Description of Common Cost Estimating Methodologies (From Naval Postgraduate School Course OA4702: Cost Estimation)

Because of the early stage of the follow-on LSD project, a parametric approach is the most appropriate technique to create the LCCE. The parametric model uses statistical methods, like single and multi-variate regression to develop Cost Estimating Relationships (CERs) based on historical quantitative inputs. The model is able to capture major portions of an estimate given a restricted amount of data from similar platforms and provides decision makers with a platform to begin a cost benefit analysis

process. Figure 1 depicts the appropriate use of modeling techniques to obtain estimates over the life of a program. Given the reasons previously mentioned, the parametric approach is useful in obtaining a ROM estimate due to the early concept phase of LSD(X).

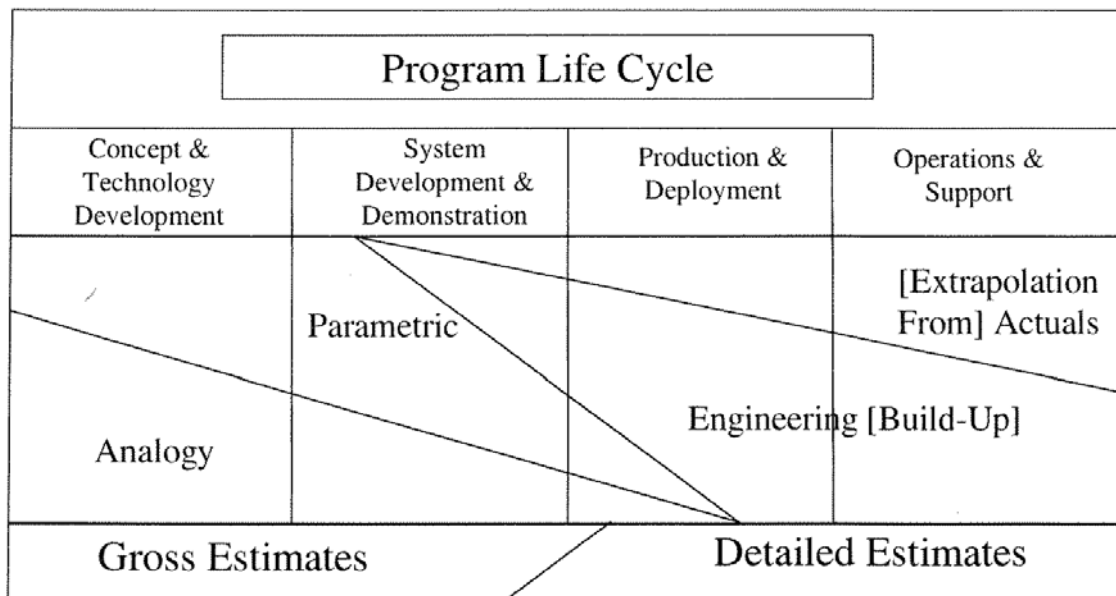


Figure 1. Depiction of the Appropriate Modeling Techniques Given Program Phase (From Naval Postgraduate School Course OA4702: Cost Estimation)

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II. LITERATURE REVIEW

A. U.S. NAVY AMPHIBIOUS FORCE

1. Mission

In the beginning of the 19th Century during the Peninsula War, the Duke of Wellington spoke of his success of his ground forces by stating “If anyone wishes to know the history of this war, I will tell them that it is our maritime superiority that gives me the power of maintaining my army while the enemy are unable to do so.” The United States has been involved in amphibious operations dating back as early as the American Revolution and continues to build a superior amphibious force. This amphibious force is capable of delivering and providing support for a Marine Expeditionary Unit at sea. Although the traditional mission revolves around sending a force ashore, a secondary mission of Humanitarian and Disaster Relief (HADR) has become increasingly important as well.

2. U.S. Navy Amphibious Ships

In order to better understand the factors that drive the LCCE of LSD(X), it is important to have a sound knowledge of the current amphibious fleet. There are presently three types of U.S. Navy Amphibious Warships, each with varying missions and capabilities. These three types are: Amphibious Assault Ships (LHA/LHD), Amphibious Transport Dock Ships (LPD), and Dock Landing Ships (LSD). Figure 2 denotes these three types.

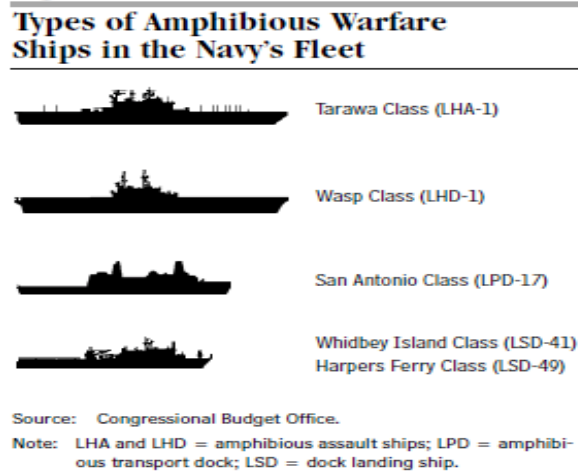


Figure 2. Types of Amphibious Warfare Ships (From Congressional Budget Office, 2011a)

The Amphibious Assault ships are typically analogous to light Aircraft Carriers in size. This group of ships includes the Wasp Class LHAs (Landing Helicopter Assault) and the Tarawa class LHDs (Landing Helicopter Dock). These ships are the centerpiece of the Amphibious Ready Group (ARG) or Expeditionary Strike Group (ESG) and are able to land and sustain forces on the ground during a time of hostility.²



Figure 3. LHA (left) and LHD (right), Amphibious Assault Ships (From Global Security Organization, 2012a and Jane's Fighting Ships, 2011)

The second group of amphibious warships is the Amphibious Transport Docks, also known as Landing Platform/Dock. The San Antonio LPDs fall under this category,

² Jane's Fighting Ships. *Amphibious Assault Ships*. Assessed October 12, 2011, <http://www4.janes.com/>.

with a main mission of transporting troops primarily via landing craft surface vessels and secondarily through helicopters. Designed as a multi-purpose ship, the LPDs are also often used for Humanitarian Assistance and Disaster Relief (HADR). The LPD does not have flag facilities and typically steams with an LHA/LHD and an LSD to comprise an ARG.



Figure 4. LPD: Amphibious Transport Dock/Landing Platform Dock (From Global Security Organization, 2011b)

The LSDs compose the Dock Landing Ship group of the Navy's amphibious force. The ships are designed to support amphibious operations via Landing Craft Air Cushion (LCAC), conventional landing craft and helicopters. As the first ship designed to embark and support four LCACs, the LSD-41 Whidbey Island class ship contributed a significant improvement in amphibious warfare.³

³ Global Security Organization, *LSD 41*, Washington D.C. Assessed October 12, 2011. <http://www.globalsecurity.org/military/systems/ship/lsd-41.htm>



Figure 5. LSD: Dock Landing Ship (From Navysite.de, 2011)

The LSD fleet is well suited to carry out Humanitarian and Disaster Relief (HADR) operations and has done so as recently as Operation Tomodachi.⁴ Operation Tomodachi assisted the country of Japan after the devastating earthquake and ensuing tsunami in March of 2011. The LSD is a multi-mission capable ship and it is evident that the future LSD(X) must continue to possess abundant war and peace time capabilities such as engaging in routine patrols overseas, reassuring allies, responding to crises and providing humanitarian aid.⁵

⁴ Commander US 7th Fleet. *Essex Embarks Japan Maritime Self-Defense Force Officer for Humanitarian Aid and Disaster Relief Coordination*, Assessed October 12, 2011, <http://www.c7f.navy.mil/news/2011/03-march/066.htm>.

⁵ Congressional Budget Office. *An Analysis of the Navy's Amphibious Warfare Ships for Deploying Marines Overseas*. (Congressional Budget Office, Washington D.C., November 2011), 4.

B. STUDIES THAT INCLUDE QUANTITATIVE ANALYSIS OF SHIP COST ESTIMATION

The following studies have been reviewed to provide a solid foundation from which to build on, but do not specifically address the limited scope of this thesis' principal research questions.

1. A Parametric Cost Model for Estimating Acquisition Costs of Conventional U.S. Navy Surface Ships

In his thesis, Loftus (1999) constructs ROM cost estimates based on historical data from 23 surface ships including small combatants, hydrofoils, cruisers, amphibious assault ships, oilers and support ships. His models predict the average procurement costs of a U.S. Naval surface ship by using the ship light displacement, the ship overall length, the ship propulsion shaft horsepower, and the number of propulsion engines as inputs.

Loftus' models only generate rough estimates with coefficients of variation between 74% and 83%; therefore the predictions may overestimate or underestimate the actual cost by more 74%. His estimates are intended to provide answers where limited data and/or engineering plans were available.

Loftus concludes that parametric models are appropriate for the production of verifiable cost estimates to be utilized to aid decision makers in determining expected program acquisition costs.

2. An Application of Data Mining Algorithms for Shipbuilding Cost Estimation

The North Atlantic Treaty Organization (NATO) Research and Technology Organization (RTO) Systems Analysis and Studies (SAS) Task group completed this study in 2011 in order to generate two independent cost estimates on the development and construction costs of the Royal Netherlands Navy Rotterdam class ships. The two methods used to produce cost estimates are the parametric approach and the analogy approach.

The parametric approach utilized the M5 model tree algorithm which included the combination of decision trees and linear regression models. The analogy approach is based on hierarchical cluster analysis and non-linear optimization. In order to analyze the results produced by these two different approaches, a database was constructed to include characteristics from 57 ships in 16 classes from six nations to include: Amphibious Assault Ships (AAS), Auxiliary Oiler Replenishment (AOR), Landing Platform Dock (LPD), Landing Platform Helicopter (LPH), Dock Landing Ship (LSD) and Icebreaker class ships.

After producing the cost estimates based on the cost and physical characteristics of the ships in the database, Kaluzny compares the estimates to the actual cost of Royal Netherlands Navy Rotterdam class ships. Kaluzny concludes that both methods are appropriate for providing accurate estimates and recommends that these methods should be considered for generating production estimates for future amphibious ships

C. CHALLENGES OF LSD(X) RECAPITILIZATION STUDY

1. Ship Procurement Rising Costs

In 2005, Congress requested that the RAND Corporation quantify the reason that ships costs were increasing at nearly double the rate of consumer inflation. The RAND report concluded that the growth in cost is equally split between economy-driven and customer-driven factors.⁶ The Navy only has control over the factors related to design complexity and requirements. In order to reduce the costs of the vessels desired, the Navy must “limit the growth in requirements and features of its ships.”⁷ The RAND Corporation report also studied the relationship between shipbuilders and cost escalation. By making improvements in efficiency and reductions in indirect costs, shipbuilders can play a role in decreasing the cost escalation of Naval Warships.⁸

⁶ RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 21.

⁷ RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 59.

⁸ RAND Corporation, *Why Has the Cost of Navy Ships Risen?* (RANDCorp., Santa Monica, CA, 2006), 71.

2. Meeting Demand given Fiscal Constraints

In order to meet the demand required by the Navy's combatant commanders, the proposed FY 2012 shipbuilding plan includes a timeline for amphibious ship procurement through 2041. The plan was analyzed by the Congressional Budget Office and a report was presented with the conclusion that the Navy would fall below the thirty ship objective during the following time periods: 2012–2016 and 2032–2041. Figure 6 presents this inventory issue utilizing the projected FY 2012 naval shipbuilding plan. If fewer ships are available and the usage demand remains the same, the ships utilized will experience a higher operational tempo and the associated costs will increase. These costs include: maintenance, fuel, and increased sea pay for the sailors.⁹ These complex scenarios and factors must be considered into the design and procurement of LSD(X) and will remain a challenge for the SEA department conducting the assessment.

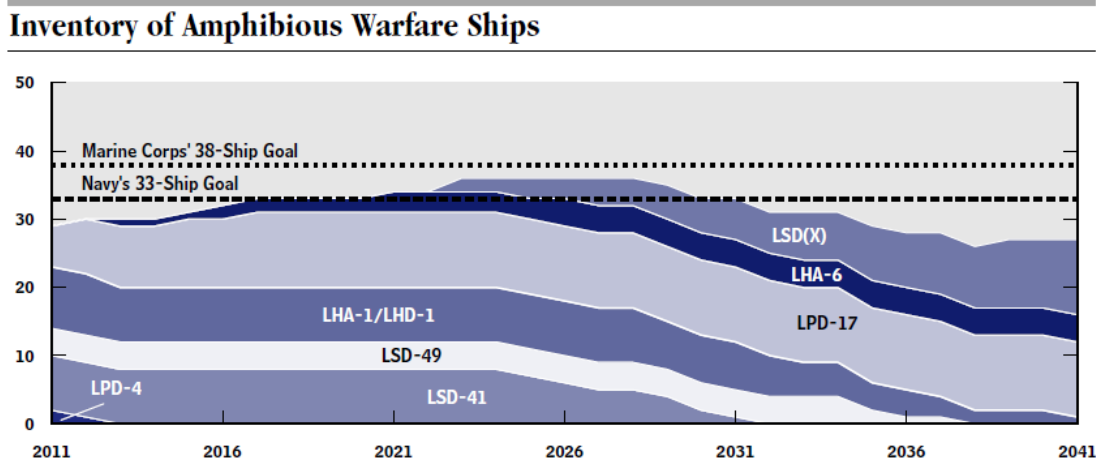


Figure 6. Projected Inventory of Amphibious Ships through FY2041 (From Congressional Budget Office, 2011b)

⁹ Congressional Budget Office. *An Analysis of the Navy's Amphibious Warfare Ships for Deploying Marines Overseas* (Congressional Budget Office, Washington D.C., November 2011), 9.

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III. METHODOLOGY

This chapter describes the parametric cost estimation approach utilized to turn raw cost and technical data into quantitative predictions. These cost estimates will be utilized by the SEA department to aid decision makers as to the best possible development of LSD(X). Chapter III describes the data set and the specific procedures and decisions required to produce an appropriate model to utilize in the estimation of LSD(X).

A. COLLECTING AND PROCESSING THE DATA SET

1. Cost Data

The cost data set compiled includes procurement cost and labor data for five amphibious warships: USS America (LHA 6), USS Wasp (LHD 1), USS Whidbey Island (LSD 41), USS Harpers Ferry (LSD 49) and the USS San Antonio (LPD 17). Each of these warships is considered a lead warship because she was the first ship built in her class. The data for each warship is divided into nine levels referred to as the Ships Work Breakdown Structure (SWBS). The SWBS is often used as a method to separate all components of a ship into groups based on function. Table 2 displays the Navy's description of SWBS at the one digit level. The one digit level SWBS for a ship is the most basic and is therefore appropriate to build a ROM estimate. As the design phase progresses, a two or three digit SWBS should be used to develop a more thorough cost estimate as further subsystems are examined.

The data set includes the costs of materials associated with each one digit SWBS level, the number of man hours utilized to produce each SWBS level, and a weight associated with SWBS levels 100–700. Levels 800 and 900 are not measured in terms of weight and are typically estimated as a percentage of SWBS 100–700.¹⁰

¹⁰ Naval Sea Systems Command Cost Engineering and Industrial Analysis Group. *Overview of Cost Estimating*. Naval Sea Systems Command Unpublished Presentation, 2008.

Ships Work Breakdown Structure (SWBS) Definitions		
100	Hull Structure	Shell plating, decks, bulkheads, framing superstructure, pressure hulls & foundations
200	Propulsion Plant	Boilers, reactors, turbines, gears, shafting propellers, steam piping and lube oil piping
300	Electric Plant	Ship service power generation equipment, power cable, lighting systems, & emergency electrical systems
400	Command & Surveillance	Navigation systems, interior communication systems, fire control systems, radars, sonars, radios, telephones, and command & control systems
500	Auxiliary Systems	Air conditioning, ventilation, refrigeration, replenishment at sea systems, anchor handling, elevators, fire extinguishing systems, distilling plants, steering systems, and aircraft launch and recovery systems
600	Outfit and Furnishing	Hull fittings, painting, insulation, berthing, sanitary spaces, offices, medical spaces, ladders, storerooms, laundry & workshops.
700	Armament	Guns, missile launchers, ammunition handling and stowage torpedo tubes, depth charges, mine handling and stowage, small arms
800	Integration/Engineering	Recurring engineering
900	Ship Assembly & Support Services	Staging, scaffolding, launching, trials, temporary utilities and services, materiel handling and removal services, and cleaning services.

Table 2. NAVSEA SWBS Breakdown (From Naval Postgraduate School Course OA4702: Cost Estimation)

The sources of data were culled from a NAVSEA database that includes the details described above producing a 45 by 3 matrix. The 45 rows each contain the 100–900 SWBS level for each of the five amphibious lead ships. The three columns contain data related to the weight in Long Tons (LT), the Materiel Cost (\$) and the Labor Hours (hrs) required to build each SWBS Level. Because the database utilized contains proprietary information, only the heading will be given in Table 3 in order to help

provide a visual basis of the data. Table 3 shows only one row of the five amphibious ships, namely USS America (LHA-6) using XXs to denote the proprietary data. The data provided for this ship is the weight, materiel cost and man hours for each of the nine one-digit SWBS Levels.

LHA-6 (SWBS Level)	Weight (LT)	Materiel Cost (\$)	Labor Hours (Hrs)
100 Hull Structure	XX LT	X.X Million	X.X Million Hrs

Table 3. Example of Data Set using the Lead Ship USS America Class (LHA-6)

2. Technical Data

The data set also includes technical parameters and attributes for each of the five classes of amphibious warships. These parameters were obtained from various publicly available sources. The lead ships included in the data set are summarized in Table 4. By developing a model that considers the impact of displacement, length, beam, draft, crew size, troop size, number of LCACs and cargo capacity of each ship, this thesis provides the SEA team with a method of testing the sensitivity of the cost estimate by varying these values they deem necessary to produce the ship that best meets the recapitalization requirements.

	Amphibious Ship	Displacement (LT)	Length (ft)	Beam (ft)	Draft (ft)	Crew Size	Troop Size	# LCAC	Cargo Capacity (Cubic Feet)
1.	LHA-6	40687.5	844.16	193.9	28.54	1124	1687	0	160000
2.	LHD-1	36876.79	847.11	140.09	26.57	1188	1687	3	125000
3.	LPD-17	23482.14	683.73	104.66	22.97	388	720	2	34000
4.	LSD-41	14459.82	609.58	84	20.67	434	402	4	5000
5.	LSD-49	15186.61	609.58	84	20.67	434	402	2	67600

Table 4. Amphibious Ship Technical Specifications After Doebling, 2012 and Jane's Fighting Ships, 2011

The final data set has been expanded to include the above technical specifications, making it a 45 by 11 matrix. Each of the five lead ships is broken down into nine level SWBS providing 45 rows (5*9). The 11 columns account for the eight technical parameters mentioned above and the inclusion of the weight, labor hours, and materiel cost data.

B. NORMALIZING THE DATA SET

In order to develop parametric cost estimates that rely on regression analysis, each data point must be carefully evaluated and properly adjusted for inflation. This inspection is necessary because the data set consists of a variety of ship classes, constructed over the past three decades.

1. Standardizing Units of Measurement and Definitions

For the purpose of this thesis, the following definitions are standardized as follows:

- Displacement, measured in Long Tons, is the full load weight of the vessel when it is loaded to maximum capacity. The measurement includes the weight of the ship and its cargo, personnel, fuel, water, stores and other items necessary for use on a transit.
- Length, measured in feet, is the overall length measured from the extreme forward end of the bow to the extreme stern.
- Beam, measured in feet, is the width of the ship at its widest point.
- Draft, measured in feet, is the vertical distance between the waterline and the bottom of the hull while the ship is in its fully loaded configuration.
- Crew Size refers to the number of personnel the ship was designed to accommodate in order to effectively man the ship to conduct all required missions.
- Troop Size refers to the number of Marines the ship was designed to transport. This size does not include the number of Marines the ship can transport in a surge capacity.
- Number of LCACs refers to the number of Landing Craft Air Cushions that may be transported on the vessel.
- Cargo Capacity, measured in cubic feet, refers to the amount of designated cargo storage on board the vessel.

2. Inflation Normalization

To normalize all dollar values for inflation, individual dollar amounts are converted into FY2012 dollars utilizing the Joint Inflation Calculator (development version 1c FY 2012). The Joint Inflation Calculator was developed by the Naval Center for Cost Analysis to provide inflation rates and indices for the Department of Defense. The JIC is publically available and may be downloaded from the Naval Center for Cost Analysis (NCCA) website at www.ncca.navy.mil. The inflation category selected for the appropriate normalization of figures in this thesis was SCN, or Shipbuilding and

Conversion, Navy. The proprietary data displayed in the example provided in Table 3 has been converted by these inflation indices to the final set of data which are used in the subsequent analysis.

3. Ship Quantity Normalization

As more ships of the same class are produced in the shipyard, the labor force becomes more experienced and the subsequent ships built become less costly. This theory is called learning. Learning is only applied to the production labor in the SWBS 100–700 groups.¹¹ Because the data set includes ships from classes with a varying number of ships in each class, only the lead ship production costs are used in order to predict the cost of the lead LSD (X) ship.

C. CONSTRUCTING THE MODEL

Now that the data set has been compiled and adjusted to account for inflation and quantity, data analysis can be used to identify relationships between cost data and technical attributes of the warships. The regression techniques used to develop a model for predicting the cost of LSD (X) are explained in the following sections.

1. Relationship Determination and Transformation

The first step is to employ linear regression techniques to the data set in order to determine if a linear relationship exists between the dependent variable and an independent variable(s). Often the relationship is non-linear and a transformation of the variables is applied to increase the statistical significance of a relationship. Transforming a variable involves using a mathematical operation to change its measurement scale. The transformations commonly applied to variables to determine if a non-linear relationship exists are the logarithmic, exponential and the power functions.

¹¹ Naval Sea Systems Command Cost Engineering and Industrial Analysis Group. *Overview of Cost Estimating*. Naval Sea Systems Command Unpublished Presentation, 2008.

2. Regression Model Generation

In order to build parametric cost models for LSD(X), the Analysis ToolPak add-in feature for Excel 2007 was used as the main regression tool to conduct Ordinary Least Squares (OLS) regression. OLS minimizes the sum of squared vertical distances between the actual responses and the predicted responses of the linear approximation.

Additional independent variables may be added in pursuit of a better model than the model resulting from single variable regression. These additional variables must not be too highly correlated in order to avoid the ramifications of multi-collinearity.

3. Model Determination

The goal is to produce a functional relationship between the dependent variables-material costs and labor hours-and one or more of the independent technical variables. In order to measure the goodness of fit of these models, the values for “P-value,” and “Adjusted R²” produced in the Full Model Report in Excel will be analyzed, using the statistical textbook by Devore as a reference¹². These statistics provide insight as to whether or not variables should be included in a model.

a. P-Value

The p-value statistic is a measure of evidence against the null hypothesis. The null hypothesis is “the factors added to the model have no influence over the dependent variables, materiel cost and labor hours.” If the null hypothesis is correct, then the materiel cost or labor hours of the LSD(X) can be better predicted by the average of the historical cost data than by the technical variables introduced. For example, when building the cost model for the materiel costs associated with the 100 SWBS level (Hull Structure), one null hypothesis to be tested is that one of the eight technical parameters (Length, Displacement, Beam, Draft, Crew Size, Troop Size, Cargo Capacity and number of LCACs) will have no influence on predicting the materiel cost of the hull structure. Because this is the null hypothesis, it must be overturned by statistical significance for it

¹² Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007.

to be disputed. A similar null hypothesis will be created for each technical factor given both labor hours and materiel cost as separate dependent variables. For a single factor model using Beam as the regressor, the model is:

$$\text{Materiel Cost (\$)} = \beta_0 + \beta_1 * \text{Beam (ft)}$$

The hypothesis can be displayed as:

H_0 (Null Hypothesis): $\beta_1 = 0$ (cost is not related to size of beam)

H_A (Alternative): $\beta_1 \neq 0$ (cost is related to size of beam)

When an Analysis of Variance (ANOVA) test is conducted, the p-value produced can be interpreted as the probability that the coefficients of the independent variables in the model are all zero. The significance level, α , is selected as a measure for determining which variables will be allowed into the model. For the purpose of this thesis we have selected an α of 0.1 to determine whether or not we accept the null hypothesis. If the P-value is ≤ 0.1 , we will reject the null hypothesis. If the P-value is > 0.1 , we will not reject the null hypothesis.

For the materiel cost versus beam model above, the excel output is provided in Figure 7. We note that the P-value (highlighted) is well below our alpha of 0.1. In this case we reject the null hypothesis that cost is not predicted by the size of the beam, and we conclude that the size of the beam of the LSD (X) will affect the materiel cost.

ANOVA								
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>			
Regression	1	3.32E+15	3.32E+15	27.99581	0.013171177			
Residual	3	3.56E+14	1.19E+14					
Total	4	3.68E+15						

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	-4.4E+07	15002894	-2.95663	0.059705	-92103898.68	3387908.6	-9.2E+07	3387909
Beam..ft.	618782.4	116947.6	5.291107	0.013171	246602.8496	990961.961	246602.8	990962

Figure 7. ANOVA Output for Beam

b. Coefficient of Determination, R^2

The coefficient of determination (R^2) evaluates the fit of the cost models created with regression. R^2 is a ratio of the explained variation to the total variation. An R^2 value of zero describes a model in which none of the variation in the model can be explained by the regressor(s) used. An R^2 value of 1 describes a regression model that fits perfectly and all variation can be attributed to the regressor(s) used in the construction of the model. The coefficient of determination can be calculated as:

$$R^2 = \frac{\text{explained variation}}{\text{total variation}} = \frac{\sum(Y_{\text{est}} - \bar{Y})^2}{\sum(Y - \bar{Y})^2}$$

where Y are the observed values for the dependent variable, \bar{Y} is the average of the observed values and Y_{est} are predicted values for the dependent variable using the regression equation¹³. For the purpose of this thesis, we determined that a R^2 value of 0.7 will be required for acceptance as a valid model.

c. Mean, Standard Deviation and Confidence Interval

For the case when a linear regression model does not meet our criteria of 0.7 R^2 and a p-value ≤ 0.1 , the mean and standard deviation of historical materiel costs or labor hours can be used for the cost or labor estimates and to construct a confidence interval around those estimates. The mean and standard deviation can be calculated by using the following formulas¹⁴:

Mean:
$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

Where the sample consists of n observations

¹³ Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

¹⁴ Jay Devore. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

Sample Standard Variance:
$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

Where the sample consists of n observations

Sample Standard Deviation:
$$s = \sqrt{s^2}$$

The standard deviation is used to help create confidence intervals around the mean using the t- distribution. The t- distribution is a continuous probability distribution that arises when estimating the mean of a normally distributed population in situations where the sample size is small. The critical value, t , can be found using a t- table using an appropriate alpha and $n-1$ degrees of freedom. Using the definitions for the mean (μ) and standard deviation (s) provided, the confidence intervals will be produced using the following formula¹⁵:

Confidence interval for μ : $(\bar{X} - t_{\alpha/2, n-1} s / \sqrt{n}, \bar{X} + t_{\alpha/2, n-1} s / \sqrt{n})$

4. Transformations to Achieve Linearity

Not all data sets are linear. Many of those that contain non-linear data can be transformed to make the data linear in order to perform regression analysis and establish the slope and intercept of the original data set while discovering relationships that may exist between the dependent and independent variables. Transformations are often applied when the data ranges over several orders of magnitude.¹⁶ For the purpose of this thesis, the Exponential, Logarithmic and Power models will be used in addition to the simple linear regression model. The Transformations of the variables are provided in Table 5.

¹⁵ Devore, Jay. *Probability and Statistics for Engineering and the Sciences* 7th Edition. Brooks/Cole, 2007

¹⁶ Kaluzny, An application of Data Mining Algorithms for Shipbuilding Cost Estimation, (Defence Research & Development Canada Centre for Operational Research & Analysis, Ottawa, CA, 2011), 4.

Method	Transformation(s)	Regression equation	Predicted value (\hat{y})
Standard linear regression	None Needed	$y = b_0 + b_1x$	$\hat{y} = b_0 + b_1x$
Exponential model	Dependent variable = $\log(y)$	$\log(y) = b_0 + b_1x$	$\hat{y} = 10^{b_0 + b_1x}$
Logarithmic model	Independent variable = $\log(x)$	$y = b_0 + b_1\log(x)$	$\hat{y} = b_0 + b_1\log(x)$
Power model	Dependent variable = $\log(y)$ Independent variable = $\log(x)$	$\log(y) = b_0 + b_1\log(x)$	$\hat{y} = 10^{b_0 + b_1\log(x)}$

Table 5. Transformations to Achieve Linearity

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IV. COST ANALYSIS

A. SINGLE VARIABLE REGRESSIONS

Our data analysis begins by determining if a relationship exists between materiel cost or labor hours and any of the eight individual technical parameter variables for each SWBS level. Each of the proposed models are transformed logarithmically, exponentially, and by using the power function as described in the previous section. Approximately 600 models are created and either rejected or accepted given the criteria outlined in Methodology chapter. If the model meets acceptance criteria ($p\text{-value} \leq 0.1$ and $R^2 \geq 0.7$) the regressor coefficients are recorded in the aggregate cost model. This process is repeated for all single variable regression models.

Of the 600 models created, Table 6 provides the 23 models remaining that meet the criteria outlined in the steps mentioned above. We accept at least one model for every SWBS level. Many of the SWBS levels have more than two models that may be appropriate for predicting the cost of $LSD(X)$.

SWBS Level	Model	Factor	P-Value	R²
100	Linear	Beam	0.01	0.9
100	Linear	Draft	0.04	0.82
100	Power	Crew	0.03	0.83
200	Linear	Beam	0.0532	0.76
200	Linear	Cargo	0.1	0.65
300	Linear	Beam	0.01	0.9
300	Power	Crew	0.04	0.79
300	Linear	Draft	0.06	0.75
400	Exp	Length	0.03	0.85
400	Exp	Troops	0.03	0.84
400	Exp	Crew	0.04	0.8
500	Log	Crew	0.02	0.88
500	Linear	Draft	0.0346	0.82
500	Linear	Beam	0.02	0.87
600	Linear	Beam	0.0384	0.81
600	Linear	Cargo	0.09	0.68
600	Linear	Draft	0.09	0.67
700	Linear	LCAC	0.03	0.85
700	Power	Cargo	0.06	0.74
800	Linear	Beam	0.1305	0.65
900	Lin	Beam	0.002	0.98
900	Exp	Displacement	0.02	0.86
900	Exp	Draft	0.02	0.89

Table 6. Acceptable Models from Single Variable Regression with Materiel Cost as Dependent Variable

Table 7 provides the results from running the same single variable regression given labor hours as the dependent variable. Because none of the regression models in the 200, 400, 500 and 700 SWBS levels met the required acceptance criteria, the mean and standard deviations will be used to develop an appropriate labor hour estimates for these SWBS levels.

SWBS Level	Model	Factor	P-Value	R^Squared
100	pwr	disp	0.06	0.75
100	pwr	troops	0.09	0.67
100	pwr	draft	0.09	0.67
300	log	disp	0.01	0.91
300	log	draft	0.01	0.9
300	log	Beam	0.02	0.89
600	Power	Disp	0.07	0.71
600	Power	Troops	0.1	0.65
800	log	crew	0.01	0.91
800	linear	Troops	0.05	0.77
800	linear	len	0.07	0.73
900	log	Disp	0.01	0.9
900	log	Draft	0.02	0.86
900	log	Troops	0.02	0.86

Table 7. Acceptable Models from Single Variable Regression with Labor Hours as Dependent Variable

B. MULTI-VARIATE REGRESSIONS

After completing single variable regression, multi-variate regression is the next step in developing our cost model. Prior to performing multi factor regression, a multi-collinearity test is conducted to determine how highly correlated the technical parameter variables are to each other. The existence of multi-collinearity can have several negative effects¹⁷ of the results of linear regression:

- The standard deviation of regression coefficients is inflated, therefore lowering the significance of the coefficients.
- The effects of each independent variable on predicting the outcome of materiel costs or labor man-hours may become difficult to interpret.

¹⁷ Naval Postgraduate School. *Unpublished Course Materiel for Course OA4702: Cost Estimation*. Naval Postgraduate School, 2012.

- A high overall R^2 value may be produced when non-significant correlated variables are present in the model, giving us false confidence in the predictive capability of the model.

To detect multi-collinearity between the eight technical ship parameters, we use the Correlation function in Excel. The results from this computation are displayed in Table 8. Unfortunately, all factors are highly correlated (.86 or higher) with the exception given to the number of LCACs per ship parameter.

A scatterplot matrix was also produced by using the Multi-Variate Correlation function in JMP statistics software (version JMP Pro 9) and is provided in Figure 8. The scatterplot matrix visually displays the correlation amongst the regressors. Because the technical parameters are all somewhat related to the overall size of the ship, a strong relationship exists between the variables, except for the “# of LCAC” variable. For example, as the length of a ship is increased, we can expect the beam and displacement to also increase. This idea is intuitive and in the case of this thesis, all independent variables used to produce the models are related to overall size of the ship.

The preferred method to remedy the multi-collinearity issue is through the inclusion of more data points. The addition of data points would produce more precise parameter estimates by lowering the standard errors produced by the regression analysis in small samples. Unfortunately, additional data was not available; therefore, the method of combining independent variables was attempted. Multiple variable combinations were input into the model in an attempt to reduce the correlation among the variables. For example: length and beam were multiplied to create a new variable called LENBEAM. After iterating through many of these combinations, it became clear that combining variables would not lower the correlation factor to an acceptable status of 0.7 or below. In addition, the combinations were complex and would not provide the SEA Curriculum students with an appropriate method for determining which dependent variable would have the greatest effect on cost. Because of these issues, multi-variate regression was deemed unacceptable for producing models to determine materiel cost and labor hours at each SWBS level.

	Disp	Length	Beam..ft.	Draft..ft.	Crew	Num Troops	#LCAC	Cargo Cap
Disp.	1							
Length	0.99175	1						
Beam..ft.	0.94797	0.907804	1					
Draft..ft.	0.995769	0.97866	0.972797	1				
Crew	0.927846	0.953627	0.861131	0.918464	1			
Num Troops	0.98876	0.998316	0.912836	0.977814	0.968655	1		
#LCAC	-0.57877	-0.48019	-0.72728	-0.61992	-0.37696	-0.47662	1	
Cargo Cap	0.896342	0.882336	0.897491	0.900568	0.905064	0.896737	0.69514	1

Table 8. Correlation Among Regressors

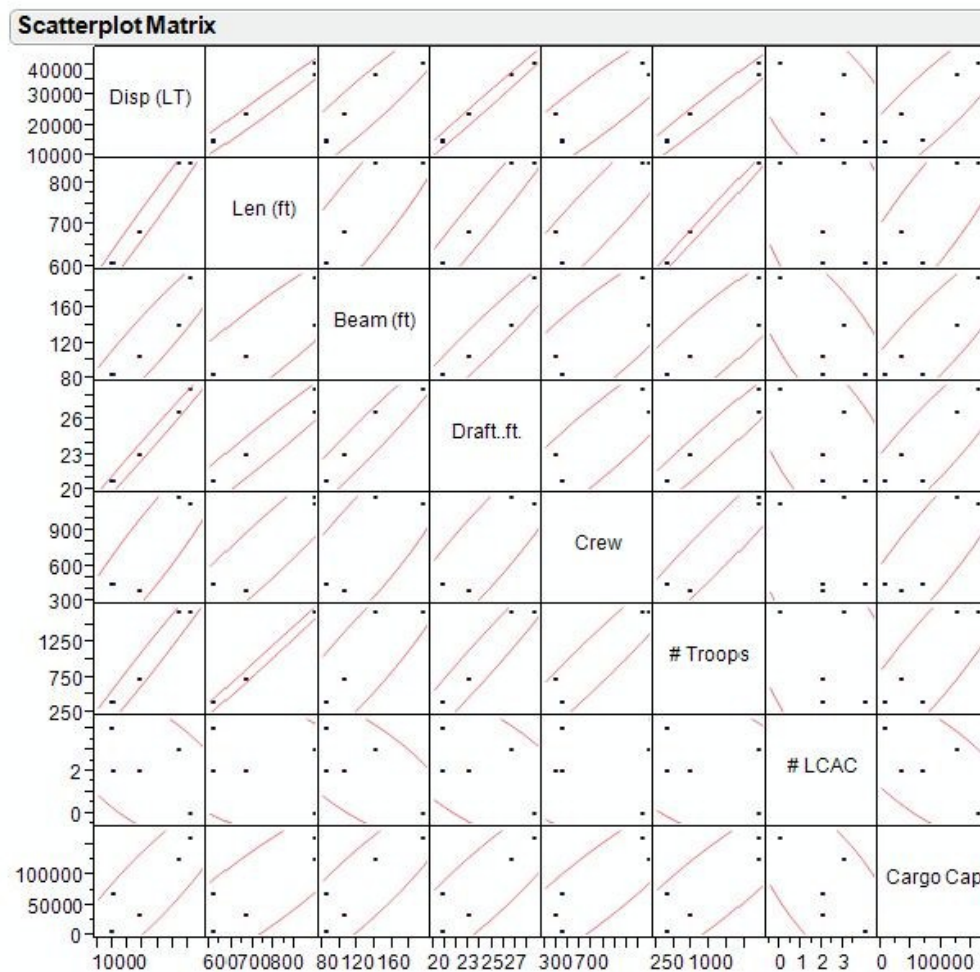


Figure 8. Multi-Collinearity Check Between Factors

C. BUILDING THE AGGREGATE MODELS

After providing the SEA Department Cost Team with the accepted single variable models discussed in Chapter IV, Part A., Figure 9 displays the variables selected for use by the SEA Department Engineering team at each SWBS level to produce the cost estimate. Of the top three best fits per SWBS level, the SEA Department Cost Team chose the regressors that would be most responsive to the five input parameters of the model, namely: Beam, Cargo Capacity, Crew Size, Troop Size, and LCAC capacity. Displacement, Length, and Draft were eliminated as descriptive variables because they were not important inputs for the SEA Curriculum engineering team. The mean labor hours value is used for SWBS 200, 400, 500, and 700 where regression on labor hours required to complete the particular SWBS level do not meet the required P-value statistic and/or R^2 value thresholds.

SWBS Level	Materiel Variables	Regression Method	Labor Variables	Regression Method
100	Beam	Linear model	Troops	Power model
200	Cargo	Linear model	Mean	-
300	Crew	Power model	Beam	Logarithmic model
400	Troops	Exponential model	Mean	-
500	Crew	Logarithmic model	Mean	-
600	Cargo	Linear model	Troops	Power model
700	LCAC	Linear model	Mean	-
800	Beam	Linear model	Crew	Logarithmic model
900	Beam	Linear model	Troops	Logarithmic model

Figure 9. Input Parameters for Estimating Materiel Costs and Labor Hours¹⁸

D. MODEL VERIFICATION

After building the aggregate model, the model was tested using procurement data from five of the Navy's current amphibious ships and the output costs of the model were

¹⁸ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

compared with the actual lead ship's cost data. Table 8 displays the input parameters and the results from the analysis. The row titled Total Cost Difference displays the difference between the actual cost of the lead ship and the cost estimated when using the model to be discussed in Section F, Design Costs. Because actual cost data is proprietary in nature, costs reflected in Table 8 are on a relative basis and utilize cost indices. In the case of LHA-6, the aggregate model underestimated the cost by 1.61 percent. The opposite is true for the Harpers Ferry (LSD-49). The model overestimated the cost of the lead ship by 11.5%. Of concern is the total cost difference produced for LPD-17. At 31.66%, the difference is outside the acceptable cost estimation standard of "less than 20%." Further research into the procurement of LPD-17 yields that the USS San Antonio was over budget and behind schedule from its inception.

"The LPD-17 program has experienced considerable cost growth, schedule delays and construction problems, particularly on the earlier ships in the program. The first ship in the program experienced cost growth of about 70%, and later ships in the program were substantially more expensive to build than originally estimated.¹⁹"

¹⁹Ronald O'Rourke. *Navy LPD 17 Amphibious Ship Procurement: Background, Issues and Options for Congress* (Washington, D.C., 2011), 4.

	Whidbey Island	Harpers Ferry	San Antonio	America	Wasp
Input Parameters	LSD-41	LSD-49	LPD-17	LHA-6	LHD-1
Number of LCACs	4	2	2	0	3
Cargo (cubic ft)	5000	50700	34000	160000	125000
Number of Crew	434	434	388	1124	1188
Number of Troops	402	402	720	1687	1687
Beam (ft)	84	84	105	194	140
Model Output Index	1.0025	1.1149	0.6834	0.9839	1.1850
Total Cost Index Historical	1.0000	1.0000	1.0000	1.0000	1.0000
Total Index Difference	0.26%	11.49%	-31.66%	-1.61%	18.50%

Table 9. Historical Lead Ship Data Compared to Costs Produced By Aggregate Model

E. LEAD SHIP COST ESTIMATES

Given the satisfactory results of the model test conducted in section E, the parameters in Table 9 were utilized to produce a cost estimate for LSD (X) and a larger variant LSD (XB). These parameters were chosen by the SEA Department Engineering Team.

	LSD(X)	LSD(XB)
Beam	90	94
LCACs	2	2
Troops	400	530
Cargo (cu ft)	20000	66000
Crew	350	380

Table 10. Initial Design Parameters Used to Obtain Lead Ship Cost Estimates²⁰

The SEA Curriculum cost team utilized a Monte Carlo Simulation to account for variations in costs to adjust the estimates to produce an estimate of the 80th percentile value of the LCCE Cumulative Distribution Function (CDF). This was done in order to ensure compliance with the Weapons Systems Acquisition Reform Act (WSARA) of

²⁰ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

2009. The WSARA of 2009 requires an 80% confidence level when providing a cost estimate in order to mitigate the risk associated with large procurement projects.²¹ Detailed information on the Monte Carlo simulation and its application can be found in Appendix C.

The output cost ranges, based on one standard deviation, for the two simulated alternatives and their respective 80th percentile CDF levels are summarized in Table 11.

Alternatives	Lower Limit	Upper Limit	80% CDF
LSD(X)	\$603.4M	\$662.5M	\$660.0M
LSD(XB)	\$771.6M	\$832.5M	\$827.9 M

Table 11. Results from 100,000 Monte Carlo Simulations for Each Lead Ship Alternative in FY12\$²²

Given the results provided in Table 10, the smaller LSD (X) alternative appears to be the least costly from a strictly procurement perspective. In order to develop the LCCEs, the design costs of the lead ship, the follow on ship costs, and the Operating and Support Costs (O&S) must be calculated and included in an additive fashion.

F. DESIGN COSTS

Recall that LCCEs consist of three phases: design, procurement, and O&S. Design costs account for the preliminary design as well as any design changes and modifications that need to be made during construction of the first ship. After speaking with industry experts, for the purpose of LSD(X), the estimated design cost to be included into the LCCE is \$350M (FY12\$).²³

²¹ H.R. 1830--111th Congress: *Weapon Systems Acquisition Reform Act of 2009*. In GovTrack.us (database of federal legislation). Accessed May 7, 2012, <http://www.govtrack.us/congress/bills/111/hr1830>

²² Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

²³ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

G. FOLLOW-ON SHIP COSTS

With the estimate of the production costs for the lead ships of LSD (X) and a larger variant LSD (XB), we use the learning curve theory to model efficiency gains introduced over the production of the 2nd through 11th ships using the formula below:

$$y_x = Tx^b$$

$$\text{Where } b = \frac{\ln \text{ of slope}}{\ln \text{ of } 2}$$

x = Hull number

y = Unit cost for hull number x

T = Lead ship cost²⁴

Initial inputs for the labor learning parameter is set at 95% while the materiel savings parameter was set at 99% as recommended by subject matter experts in the shipbuilding cost estimate field and agreed upon by the SEA Curriculum. This adjustment allows for changes in both parameters to test for sensitivity.²⁵

H. OPERATING AND SUPPORT COSTS

Finally, the O&S costs must be included into the LCCE. In order to do this, we reference the historical O&S data included on the VAMOSC Database (www.vamosc.navy.mil) of NCCA. The O&S costs provided in Table 12 account for the operation and support of one US Amphibious ship for one year and have been adjusted for inflation and converted to FY12 dollars.

²⁴ Naval Postgraduate School. *Unpublished Course Materiel for Course OA4702: Cost Estimation*. Naval Postgraduate School, 2012.

²⁵ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

Historical O&S Data Averages(FY12\$M)				
	Total O&S	Manpower	Operations	Support
LHA-1 Class	\$157.8M	\$89.4M	\$30.8M	\$37.6M
LHD-1 Class	\$157.8M	\$86.8M	\$28.6M	\$42.3M
LSD-41 Class	\$65.1M	\$23.5M	\$8.0M	\$33.6M
LSD-49 Class	\$56.9M	\$23.7M	\$9.6M	\$23.6M
LPD-4 Class	\$64.3M	\$29.3M	\$14.9M	\$20.1M
LPD-17 Class	\$49.6M	\$28.2M	\$6.5M	\$14.9M

Table 12. Historical O&S Data for Various US Amphibious Ships²⁶

Because LSD(X) is expected to conduct similar operations to the current LSD fleet (LSD-41 and LSD-49), an average of the O&S values is used to calculate the O&S costs for LSD (X). To estimate the alternative larger variant LSD(XB), we add 10% to the average to account for the larger ship size and crew size. Table 13 displays the O&S costs for both variants used in the calculation of the LCCE.

Alternatives O&S	
Alternative	FY 12\$ (M)
LSD(X)	61.0
LSD(XB)	67.1

Table 13. O&S Cost Estimates for LSD(X) and LSD(XB)²⁷

I. TOTAL LIFE-CYCLE COST ESTIMATE

In order to calculate the total LSD(X) and LSD(XB) LCCE, we add the procurement costs for each additional ship procured with the O&S costs for each ship currently operating. These procurement costs are presented in Table 13 and include the design costs discussed in section F.

²⁶ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

²⁷ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

New Construction (FY12\$ M)		
Hull #	LSD(X)	LSD(XB)
1	1010.0	1177.9
2	633.0	795.2
3	617.8	776.8
4	607.3	764.1
5	599.3	754.4
6	592.8	746.6
7	587.4	740.0
8	582.8	734.4
9	578.8	729.5
10	575.2	725.2
11	572.0	721.3

Table 14. New Construction Procurement Costs Calculated Utilizing the Learning Curve Theory Described in Section G

Based on the procurement costs for each ship and the O&S costs for a 30 year period the LCCE for the LSD(X) is \$20.37 Billion and \$23.42 Billion for LSD(XB). These figures include the assumption that 11 new construction LSD(X) or LSD(XB) class ships are purchased at an interval of one ship every other year during a 22-year period. O&S costs are included annually for each ship in operation. Table 15 provides an example of the LCCE calculation for years 1–7 and Table 16 provides a breakdown of the total LCCE calculations.

Year	1	2	3	4	5	6	7
LSD(X)	1		2		3		4
Procurement Cost	1010.00		633.00		617.80		607.30
	61.00	61.00	61.00	61.00	61.00	61.00	61.00
			61.00	61.00	61.00	61.00	61.00
					61.00	61.00	61.00
							61.00
Cost per Year	1071.0	61.00	755.00	122.00	800.80	183.00	851.30
Cumulative LCCE	1071.00	1132.00	1887.00	2009.00	2809.80	2992.80	3844.10

Table 15. Example of LCCE Calculation for years 1-7

	O&S	Procurement	Cumulative LCCE
LSD(X)	\$13,412,524,400	\$6,956,541,749	\$20,369,066,149
LSD(XB)	\$14,753,776,840	\$8,665,338,641	\$23,419,115,481

Table 16. Example of LCCE Calculation Over 30 Year Operating Period

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V. CONCLUSIONS

A. SUMMARY

As a summary of key findings of this thesis, a recap of procurement costs estimates for the LSD (X) and LSD(XB) lead ship costs in FY12\$ is provided below in Table 17.

	Design Costs	Procurement	Lead Ship Procurement
LSD(X)	\$350M	\$660M	\$1010M
LSD(XB)	\$350M	\$828.9M	\$1177.9M

Table 17. Lead Ship Procurement Costs for LSD(X) and LSD(XB)

Accounting for learning curve theory and Operating and Support (O&S) costs over a 30 year period generates our LCCE. The LCCE for LSD (X) is \$20.37 billion and \$23.42 Billion for LSD(XB) in FY\$12 dollars and is displayed in Table 18. Included in these figures is the assumption that 11 new construction LSD ships will be purchase at an interval of one ship every other year over a 22-year time frame.

	O&S	Procurement	Cumulative LCCE
LSD(X)	\$13,412,524,400	\$6,956,541,749	\$20,369,066,149
LSD(XB)	\$14,753,776,840	\$8,665,338,641	\$23,419,115,481

Table 18. Example of LCCE Calculation Over 30 Year Operating Period

Overall, the analysis within this thesis provides the Systems Engineering Analysis Curriculum students with a reliable and justifiable tool to conduct an analysis of alternatives for the LSD fleet recapitalization. These models are simple and effective and allow the user to update the final LCCE as more information on technical composition is made available. By employing the aggregate model provided from this study, the

Systems Engineering Analysis Curriculum students are able to respond to the request from OPNAV N8F by shedding light on the expected costs associated with the procurement of a new LSD fleet.

B. AREAS FOR IMPROVEMENT

The strength of the aggregate model lies with the fact that a credible and defensible cost estimate can be obtained, given technical parameter characteristics of a new amphibious ship. As displayed in the comparison between LSD(X) and LSD(XB), the aggregate model is sensitive and responsive to minimal parameter changes. This fact allows the model to be an effective tool for decision makers. Conversely, the model was only constructed using five data points and eight technical parameters. The lack of data points and small number of technical parameters led to an unavoidable and unfixable multi-collinearity issue. If more data is not available on the lead ship costs of amphibious ships, one answer may be to look into adding additional technical parameters and removing some of the other parameters that are highly correlated. Another option to obtain more data points and eliminate multi-collinearity may be to include ships classes like carriers, cruisers, destroyers, or auxiliary ships, and assign a scaling factor to account for differences in mission and composition.

C. RECOMMENDATIONS FOR FUTURE ANALYSIS

Given the results provided by this thesis as well as the SEA Curriculum recommendations for the follow-on LSD, a future study can be conducted when the Navy makes the decision and constructs the follow-on LSD ship. The technical parameters of the new ship can be used as inputs into the model created and described in this thesis. A comparison can be made between the difference of the estimate and the actual procurement cost of the new ship. This difference will give insight as to what parameters should or should not have been included in the model. Because cost estimates are necessary for each and every system acquisition and at every milestone review, further insight and analysis to developing and refining adequate prediction models will always be compulsory.

APPENDIX A. AGGREGATED MATERIEL COST REGRESSION MODELS

This section shows the details of the nine separate parametric cost models used to build the aggregate cost model for the materiel cost estimate. These models represent the most responsive models for each SWBS level.

SWBS Level	Materiel Variables	Regression Method	P-Value	R ² Value
100	Beam	Linear	0.01	0.9
200	Cargo Cap	Linear	0.01	0.65
300	Crew	Power	0.04	0.79
400	Troops	Exponential	0.03	0.84
500	Crew	Logarithmic	0.02	0.88
600	Cargo Cap	Linear	0.09	0.68
700	LCAC	Linear	0.03	0.85
800	Beam	Linear	0.13	0.59
900	Beam	Linear	0.002	0.98

Table 19. Aggregate Materiel Cost Model per SWBS

A. REGRESSION MODEL 1: MATERIEL COST VS BEAM

Material Cost (at 100 SWBS) = - 44,357,995.04 + 618,782.41*Beam (ft)

Regression Statistics					
Multiple R	0.950375046				
R Square	0.903212728				
Adjusted R Square	0.870950304				
Standard Error	10897667.7				
Observations	5				
ANOVA					
	df	SS	MS	F	Significance F
Regression	1	3.32476E+15	3.325E+15	27.995811	0.013171177
Residual	3	3.56277E+14	1.188E+14		
Total	4	3.68104E+15			
	Coefficients	Standard Error	t Stat	P-value	
Intercept	-44357995.04	15002893.71	-2.9566293	0.0597055	
Beam..ft.	618782.4053	116947.6309	5.2911068	0.0131712	

Figure 10. Details of Regression Model for 100 SWBS Materiel Cost

B. REGRESSION MODEL 2: MATERIEL COST VS CARGO CAPACITY

Material Cost (at 200 SWBS) = + 14,825,686.83+632.92* Cargo Capacity (CuFt)

Regression Statistics					
Multiple R	0.808518				
R Square	0.6537014				
Adjusted R Square	0.5382685				
Standard Error	33961747				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	6.53176E+15	6.532E+15	5.6630442	0.09764294
Residual	3	3.4602E+15	1.153E+15		
Total	4	9.99196E+15			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	14825687	25779405.57	0.5750981	0.6055234	
Cargo.Capacity	632.91585	265.9628595	2.3797152	0.0976429	

Figure 11. Details of Regression Model for 200 SWBS Materiel Cost

C. REGRESSION MODEL 3: MATERIEL COST VS. CREW

$$\text{Materiel Cost (at 300 SWBS)} = 10^{2.2142+1.8789(\text{Crew})}$$

Regression Statistics					
Multiple R	0.890416				
R Square	0.7928407				
Adjusted R Square	0.7237876				
Standard Error	0.2692641				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.83245293	0.8324529	11.48161	0.04282365
Residual	3	0.217509456	0.0725032		
Total	4	1.049962385			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	2.2141612	1.556119239	1.4228737	0.2499349	
log crew	1.8789323	0.554510446	3.3884525	0.0428237	

Figure 12. Details of Regression Model for 300 SWBS Materiel Cost

D. REGRESSION MODEL 4: MATERIEL COST VS. TROOPS

Materiel Cost (at 400 SWBS Level) = $10^{6.9371+0.0006(\text{Troops})}$

Regression Statistics					
Multiple R	0.91794529				
R Square	0.84262355				
Adjusted R Square	0.79016473				
Standard Error	0.21270322				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.726713538	0.7267135	16.062573	0.0278657
Residual	3	0.135727986	0.0452427		
Total	4	0.862441524			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	6.93711711	0.184567655	37.585768	4.143E-05	
X..Troops	0.0006471	0.00016146	4.0078139	0.0278657	

Figure 13. Details of Regression Model for 400 SWBS Materiel Cost

E. REGRESSION MODEL 5: MATERIEL COST VS. CREW

Material Cost (at the 500 SWBS level) =- 717,242,801.49+ 290,685,674.30 *log(crew)

Regression Statistics					
Multiple R	0.9388732				
R Square	0.881483				
Adjusted R Square	0.8419773				
Standard Error	29882379				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	1.9924E+16	1.992E+16	22.312814	0.01797456
Residual	3	2.6789E+15	8.93E+14		
Total	4	2.2603E+16			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	-717242801	172694935	-4.1532359	0.0253724	
log Crew	290685674	61538436.8	4.7236441	0.0179746	

Figure 14. Details of Regression Model for 500 SWBS Materiel Cost

F. REGRESSION MODEL 6: MATERIEL COST VS. CARGO CAPACITY

Matériel Cost (at 600 SWBS level) = 11,504,903.36 + 346.58(Cargo Capacity)

Regression Statistics					
Multiple R	0.8217078				
R Square	0.6752037				
Adjusted R Square	0.5669382				
Standard Error	17721631				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	1.95863E+15	1.959E+15	6.2365578	0.08791494
Residual	3	9.42169E+14	3.141E+14		
Total	4	2.9008E+15			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	11504903	13451991.1	0.8552565	0.4552765	
Cargo Capacity CU f	346.58291	138.782487	2.4973101	0.0879149	

Figure 15. Details of Regression Model for 600 SWBS Matériel Cost

G. REGRESSION MODEL 7: MATERIEL COST VS. # OF LCAC

Materiel Cost (at the 700 SWBS level) = 4,380,774.00 - 1,006,470.18 (# LCAC)

Regression Statistics					
Multiple R	0.9197818				
R Square	0.8459986				
Adjusted R Square	0.7946648				
Standard Error	735460.05				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	8.91424E+12	8.914E+12	16.480346	0.02694306
Residual	3	1.6227E+12	5.409E+11		
Total	4	1.05369E+13			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	4380774	636927.0874	6.8779835	0.0062949	
Num LCAC	-1006470.2	247923.5325	-4.0595992	0.0269431	

Figure 16. Details of Regression Model for 700 SWBS Materiel Cost

H. REGRESSION MODEL 8: MATERIEL COST VS. BEAM

Material Cost (at the 800 SWBS level) = - 17,340,842.70 + 527,018.93(Beam)

Regression Statistics					
Multiple R	0.76663252				
R Square	0.58772543				
Adjusted R Square	0.45030057				
Standard Error	23747273.6				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	2.4118E+15	2.412E+15	4.2767039	0.13048936
Residual	3	1.6918E+15	5.639E+14		
Total	4	4.1036E+15			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	-17340843	32693034	-0.530414	0.632578	
Beam..ft.	527018.929	254842.362	2.0680193	0.1304894	

Figure 17. Details of Regression Model for 800 SWBS Materiel Cost

I. REGRESSION MODEL 9: MATERIEL COST VS. BEAM

Matériel Cost (at the 900 SWBS level) = - 45,899,595.03+573,307.33(Beam)

Regression Statistics					
Multiple R	0.9877649				
R Square	0.9756796				
Adjusted R Square	0.9675727				
Standard Error	4869688.7				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	2.854E+15	2.854E+15	120.35298	0.0016216
Residual	3	7.1142E+13	2.371E+13		
Total	4	2.9252E+15			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	-45899595	6704133.74	-6.8464617	0.006378	
Beam..ft.	573307.33	52258.7557	10.970551	0.0016216	

Figure 18. Details of Regression Model for 900 SWBS Matériel Cost

APPENDIX B. AGGREGATED LABOR REGRESSION MODELS

This section shows the details of the nine separate parametric cost models used to build the aggregate cost model for the labor hours estimate. These models represent the most responsive models for each SWBS level.

SWBS Level	Labor Variables	Regression Method	P-Value	R ² Value
100	Troops	Power	0.09	0.67
200	Mean	-		
300	Beam	Logarithmic	0.02	0.89
400	Mean	-		
500	Mean	-		
600	Troops	Power	0.1	0.65
700	Mean	-		
800	Crew	Logarithmic	0.01	0.91
900	Troops	Logarithmic	0.02	0.86

Table 20. Aggregate Labor Hour Model per SWBS

A. REGRESSION MODEL 1: LABOR HOURS VS. TROOPS

Labor Hours (at the 100 SWBS level) = $10^{4.4132+0.6606\log(\text{troops})}$

Regression Statistics					
Multiple R	0.8193639				
R Square	0.6713571				
Adjusted R Square	0.5618095				
Standard Error	0.1667906				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.170487913	0.1704879	6.1284497	0.0896208
Residual	3	0.08345728	0.0278191		
Total	4	0.253945193			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	4.4131573	0.778470594	5.6690096	0.0108723	
log Num Troops	0.6605682	0.266834714	2.4755706	0.0896208	

Figure 19. Details of Regression Model for 100 SWBS Labor Hours

B. REGRESSION MODEL 2: LABOR HOURS VS. BEAM

Labor Hours (at the 300 SWBS level) = - 8,145,294.16+ 4,436,844.02*log(beam)

Regression Statistics					
Multiple R	0.943998				
R Square	0.8911322				
Adjusted R Square	0.8548429				
Standard Error	279880.01				
Observations	5				
ANOVA					
	df	SS	MS	F	Significance F
Regression	1	1.92357E+12	1.924E+12	24.556358	0.01577455
Residual	3	2.34998E+11	7.833E+10		
Total	4	2.15857E+12			
	Coefficients	Standard Error	t Stat	P-value	
Intercept	-8145294.2	1849075.624	-4.4050628	0.0216964	
log beam	4436844	895348.6573	4.9554372	0.0157746	

Figure 20. Details of Regression Model for 300 SWBS Labor Hours

C. REGRESSION MODEL 3: LABOR HOURS VS. TROOPS

Labor Hours (at the 600 SWBS level) = $10^{2.84+1.12\log(\text{troops})}$

Regression Statistics					
Multiple R	0.8078277				
R Square	0.6525855				
Adjusted R Square	0.5367807				
Standard Error	0.2958864				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	0.4933566	0.4933566	5.6352193	0.09816063
Residual	3	0.26264635	0.0875488		
Total	4	0.75600296			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	2.8390904	1.38100671	2.0558122	0.1320252	
log Num Troops	1.1237024	0.47336474	2.3738617	0.0981606	

Figure 21. Details of Regression Model for 600 SWBS Labor Hours

D. REGRESSION MODEL 4: LABOR HOURS VS. CREW

Labor Hours (at the 800 SWBS level) = - 24,430,121.22+ 9,778,347.63*log(crew)

Regression Statistics					
Multiple R	0.953709				
R Square	0.9095609				
Adjusted R Square	0.8794145				
Standard Error	864442				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	2.25459E+13	2.255E+13	30.171483	0.011872436
Residual	3	2.24178E+12	7.473E+11		
Total	4	2.47877E+13			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	-24430121	4995745.294	-4.8901855	0.0163567	
log Crew	9778347.6	1780193.241	5.4928574	0.0118724	

Figure 22. Details of Regression Model for 800 SWBS Labor Hours

E. REGRESSION MODEL 5: LABOR HOURS VS. TROOPS

Labor Hours (at the 900 SWBS level) = - 11,271,570.35 + 4,872,618.37*log(troops)

<i>Regression Statistics</i>					
Multiple R	0.9262458				
R Square	0.8579312				
Adjusted R Square	0.810575				
Standard Error	715573.1				
Observations	5				
ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	9.2765E+12	9.276E+12	18.116533	0.02377663
Residual	3	1.5361E+12	5.12E+11		
Total	4	1.0813E+13			
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	
Intercept	-11271570	3339832.87	-3.3748905	0.0432542	
log Num Troops	4872618.4	1144787.42	4.2563521	0.0237766	

Figure 23. Details of Regression Model for 900 SWBS Labor Hours

APPENDIX C. MONTE CARLO SIMULATIONS

Monte Carlo simulation techniques are used in this thesis for estimating uncertainty for cost of the lead ships. Monte Carlo simulations are computational algorithms that rely on repeated random sampling to compute their results. These simulations were used to account for variations in the design, construction, and cost estimating processes. The following documentation was provided by the Systems Engineering Analysis Curriculum Students on the use of Monte Carlo Simulations²⁸:

Introduction: The American Association of Cost Engineers (AACE) defines cost engineering as “that area of engineering practice where engineering judgment and experience are utilized in the application of scientific principles and techniques to the problems of cost estimation, cost control, and profitability.” (AACE International, 2011) Cost estimation essentially uses the plan of a project and maps it to a dollar value by applying appropriate costs to the quantities identified in the plan, and in this case, gives insight into how much a lead ship would cost. However, it must be noted that figures derived via this process are predictions at best due to the fundamentally uncertain nature of cost estimation. This uncertainty stems from the following two categories (Fisher, 1962):

Requirements Uncertainty: This refers to the variability in cost estimates due to changes in the configuration of the system being estimated. As an example, suppose that, at present, the analysis of system configurations for each ship suggested an optimal loading capacity of 1000 troops. While valid under present day circumstances, this requirement may change further down the acquisition/manufacturing process, thereby rendering cost estimates incorrect. While the example cited specifications of the ship, this uncertainty may also apply to hardware characteristics and/or operational concepts.

Cost-Estimating Uncertainty: This refers to variations in cost estimates of a system even though the original configuration remains unchanged. This variation may arise from errors in the data base, errors or inappropriateness of cost estimating techniques, insufficient data for building the costing model, and the inherent uncertainty of the cost model, as identified, for example in the statistics such as Standard Error of the Estimates (SEE).

²⁸ Naval Postgraduate School. *Unpublished Systems Engineering Analysis Curriculum Cost Estimation Report for LSD Capabilities Based Assessment*. Naval Postgraduate School, 2012.

The relationship between the system cost uncertainty and its sources can be depicted using the display in Figure 24.

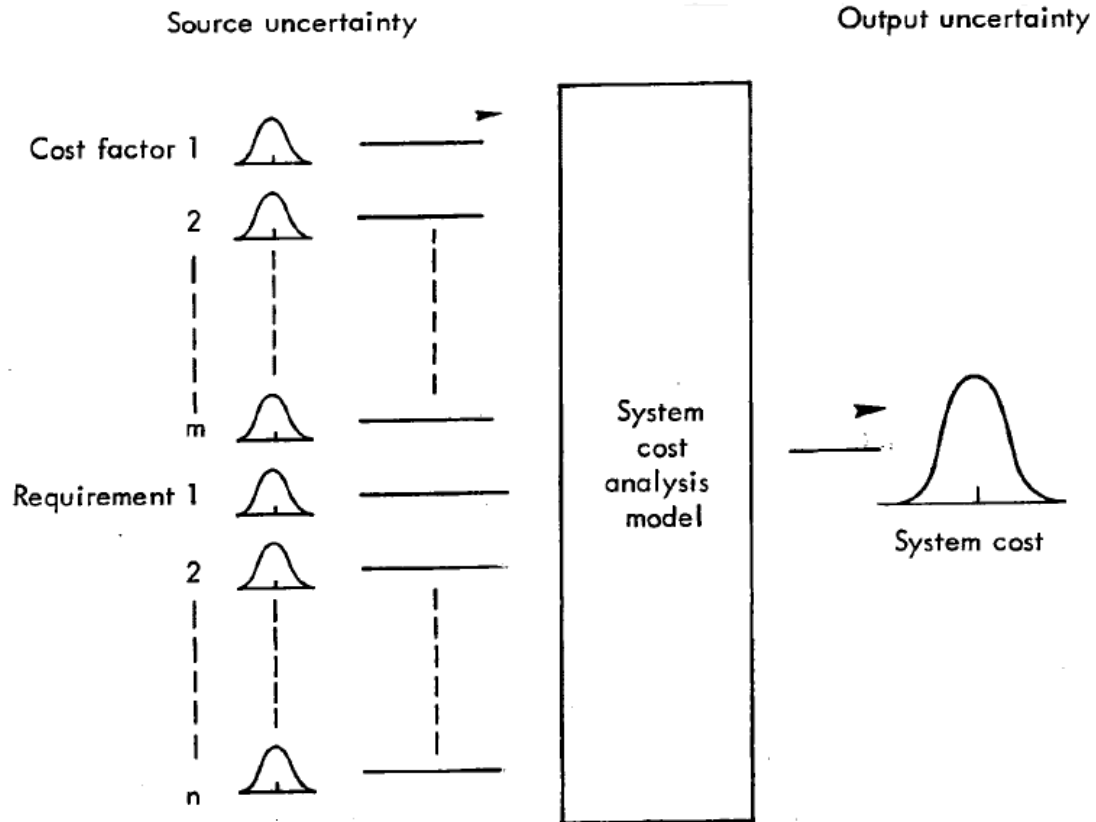


Figure 24. Relation of System Cost Uncertainty to Source Uncertainty (From Dienemann, 1966)

Associated with each cost input is a probability distribution to reflect its uncertainty. Given that each input parameter is described with a probability distribution, the distribution is then treated as a theoretical population from which random samples are taken, and which are used to develop an aggregated LCCE distribution. This technique is referred to as Monte Carlo simulation.

Methodology: A Monte Carlo simulation was run for each cost component, i.e. for materiel costs and for labor costs. The steps are detailed below.

a. Identifying Probability Distribution. The first step involves identifying the parameters of a suitable probability distribution. Given the limited data points in creating the regression model for each SWBS level, it was decided that using a Triangle distribution²⁹ would be appropriate.

b. Deriving Parameters. As mentioned in Section 5, each SWBS level had a regression model built, to estimate either materiel costs or labor hours, as a function of only one regressor. Let this model be termed $f(x)$. The range of this regressor was obtained from the data set and three values in this range were passed through the regression model to obtain the parameters for the Triangle distribution, namely, the lowest value over the range a to obtain parameter $f(a)$, the highest value over the range c to obtain parameter $f(c)$ and the most likely value b to obtain parameter $f(b)$. Fig 25 illustrates this procedure.

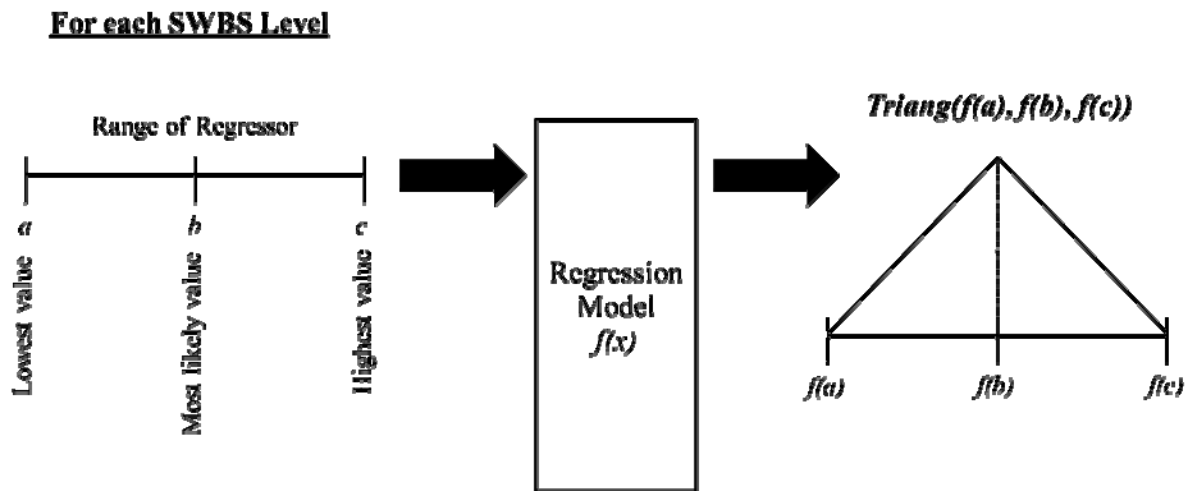


Figure 25. Procedure for Derivation of Parameters

²⁹ *Tri* (a, b, c) where a corresponds with the lowest value, c corresponds with the highest value and b corresponds with the most likely value.

A. LSD(X) ALTERNATIVE

The following methodology applies to estimates for alternatives that involve utilizing a newly designed ship hull form for the project. These alternatives that use this include: LSD(X) and LSD(XB). The ranges of the regressors used as input parameters to estimate the cost of the LSD(X) Small Variant are shown in Table 21.

Regressor	Lowest Value	Most Likely Value	Highest Value
Beam	81	90	99
LCACs	1	2	3
Troops	340	400	460
Cargo (cuft)	17000	20000	23000
Crew	298	350	403

Table 21. Range of Values for Regressors – LSD(X)

The final probability distributions for materiel costs and labor hours are shown below.

SWBS Level	Regressor	Lowest Value	Most Likely Value	Highest Value
100	Beam	5763380	11332421	16901463
200	Cargo	25585255	27484003	29382750
300	Crew	7295348	9869447	12863317
400	Troops	14359267	15702126	17170568
500	Crew	1976422	22281333	40082053
600	Cargo	17396813	18436561	19476310
700	LCAC	3374304	2367834	1361364
800	Beam	25347691	30090861	34834031
900	Beam	538299	5698065	10857831

Table 22. Probability Distributions for Materiel Costs – LSD(X)

SWBS Level	Regressor	Lowest Value	Most Likely Value	Highest Value
100	Troops	1217227	1355175	1486245
200	Mean	307295	307295	307295
300	Beam	322356	525375	709028
400	Mean	453541	453541	453541
500	Mean	2243576	2243576	2243576
600	Troops	482747	579471	678013

700	Mean	50235	50235	50235
800	Crew	-236374	446661	1045457
900	Troops	1063360	1407275	1703032

Table 23. Probability Distributions for Labor Hours – LSD(X)

Simulation Results. 100,000 simulations were run for each cost component with the following results:

a. Material Costs. The simulations resulted in a mean of \$142.6M with a standard deviation of \$8.7M. This resulted in a range of between \$133.8M and \$151.3M based on one standard deviation. The results of the Monte Carlo simulation are shown in Fig 26. The corresponding 80% CDF level is approximately \$150M.

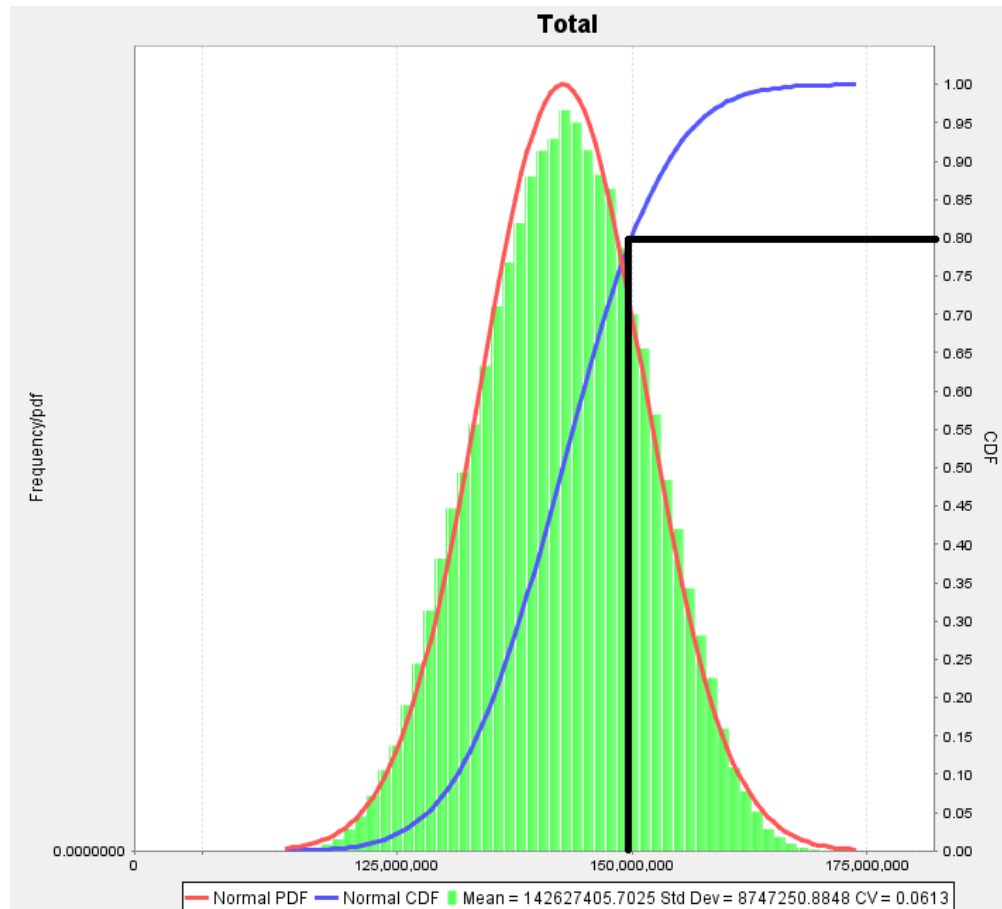


Figure 26. Results of Monte Carlo Simulation for Materiel Costs – LSD(X)

b. Labor Hours. The simulations resulted in a mean 7.3M hours, with a standard deviation of 310,118 hours. After factoring in the recommended labor rate of \$67.02 per hour, the range for the total cost of labor was between \$469.6M and \$511.1M based on one standard deviation. The results of the Monte Carlo simulation are shown in Fig 27. The corresponding 80% CDF level is approximately 7.6M hours, or \$510.0M after factoring in labor rates.

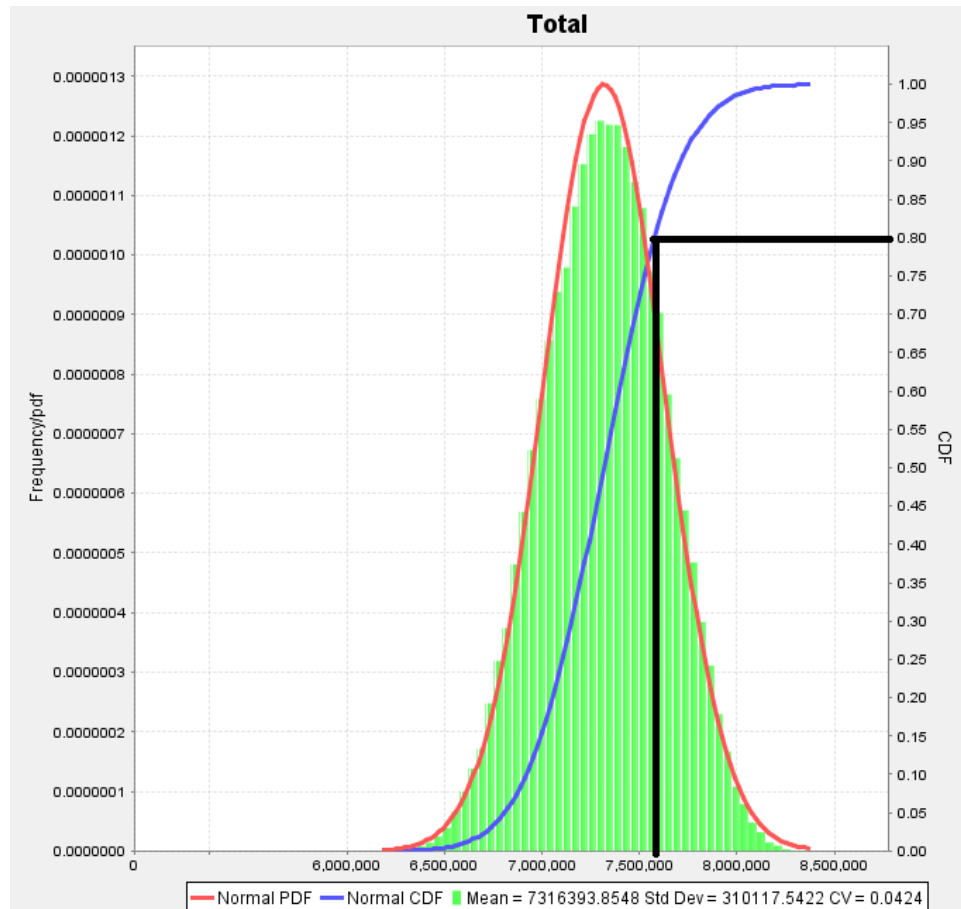


Figure 27. Results of Monte Carlo Simulation for Labor Hours – LSD(X)

Monte Carlo simulation yielded a total cost range of between \$603.4M and \$662.5M based on one standard deviation for the LSD(X) Small variant. The 80% CDF level is \$660M.

B. LSD(XB) THE LARGER NEW CONSTRUCTION ALTERNATIVE

The ranges of the regressors used as input parameters to estimate the cost of the LSD(XB) Variant are shown in Table 24.

Regressor	Lowest Value	Most Likely Value	Highest Value
Beam	84.6	94	103.4
LCACs	1	2	3
Troops	451	530	610
Cargo (cuft)	56100	66000	75900
Crew	323	380	437

Table 24. Range of Values for Regressors – LSD(XB)

The final probability distributions for materiel costs and labor hours are shown below.

SWBS Level	Regressor	Lowest Value	Most Likely Value	Highest Value
100	Beam	7990996	13807551	19624106
200	Cargo	50332263	56598130	62863996
300	Crew	8487560	11518606	14977766
400	Troops	16941846	19058201	21470896
500	Crew	12146426	32663333	50307325
600	Cargo	30948204	34379375	37810545
700	LCAC	3374304	2367834	1361364
800	Beam	27244959	32198937	37152915
900	Beam	2602205	7991294	13380383

Table 25. Probability Distributions for Materiel Costs – LSD(XB)

SWBS Level	Regressor	Lowest Value	Most Likely Value	Highest Value
100	Troops	1466972	1632027	1790843
200	Mean	307295	307295	307295
300	Beam	406148	609166	792819
400	Mean	453541	453541	453541
500	Mean	2243576	2243576	2243576
600	Troops	663124	794998	931048
700	Mean	50235	50235	50235
800	Crew	105733	795900	1389424
900	Troops	1661219	2002786	2300279

Table 26. Probability Distributions for Labor Hours – LSD(XB)

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